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Hu, Hao; Kong, Deming; Palushani, Evarist; Galili, Michael; Mulvad, Hans Christian Hansen; Oxenløwe, Leif Katsuo

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# 320 Gb/s Nyquist OTDM received by polarization-insensitive time-domain OFT

H. Hu,<sup>1,\*</sup> D. Kong,<sup>1,2</sup> E. Palushani,<sup>1</sup> M. Galili,<sup>1</sup> H. C. H. Mulvad,<sup>1</sup> and L. K. Oxenløwe<sup>1</sup>

<sup>1</sup>DTU Fotonik, Department of Photonics Engineering, Technical University of Denmark, Ørstedss Plads, Building 343, DK-2800 Kgs. Lyngby, Denmark

<sup>2</sup>State Key Laboratory of Information Photonics and Optical Communications, Beijing University of Posts and Telecommunications, Beijing, 100876, China  
[huhao@fotonik.dtu.dk](mailto:huhao@fotonik.dtu.dk)

**Abstract:** We have demonstrated the generation of a 320 Gb/s Nyquist-OTDM signal by rectangular filtering on an RZ-OTDM signal with the filter bandwidth (320 GHz) equal to the baud rate (320 Gbaud) and the reception of such a Nyquist-OTDM signal using polarization-insensitive time-domain optical Fourier transformation (TD-OFT) followed by passive filtering. After the time-to-frequency mapping in the TD-OFT, the Nyquist-OTDM signal with its characteristic sinc-shaped time-domain trace is converted into an orthogonal frequency division multiplexing (OFDM) signal with sinc-shaped spectra for each subcarrier. The subcarrier frequency spacing of the converted OFDM signal is designed to be larger than the transform-limited case, here 10 times greater than the symbol rate of each subcarrier. Therefore, only passive filtering is needed to extract the subcarriers of the converted OFDM signal. In addition, a polarization diversity scheme is used in the four-wave mixing (FWM) based TD-OFT, and less than 0.5 dB polarization sensitivity is demonstrated in the OTDM receiver.

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**OCIS codes:** (060.2330) Fiber optics communications; (060.4230) Multiplexing; (070.4340) Nonlinear optical signal processing; (070.1170) Analog optical signal processing.

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## 1. Introduction

With the exponential growth of network traffic, the demand for communication capacity is increasing dramatically [1]. There is a great interest in increasing the spectral efficiency (SE) of data signals in order to achieve larger capacity within the limited bandwidth of optical amplifiers (~5 THz for typical EDFAs). Various approaches have been investigated, such as advanced modulation formats, space division multiplexing and spectrally-efficient channel

multiplexing [1–6]. Nyquist WDM and orthogonal frequency division multiplexing (OFDM) have been proposed since both of these can combine multiple channels with high SE and achieve a channel spacing equal to the symbol rate. Nyquist WDM consists of multiple WDM channels having rectangular spectra with bandwidth equal to the baud rate and sinc-shaped pulses in the time domain [7,8]. The alternative approach, OFDM, uses sinc-shaped and orthogonally overlapped sub-carriers to tightly multiplex data signals in frequency [9,10].

Optical time division multiplexing (OTDM), in which data streams are encoded on short optical pulses at the same wavelength and then multiplexed in time, has been demonstrated at the very high bit rates of 5.1 Tb/s or 9.5 Tb/s using either direct or coherent detection [11,12]. However, OTDM relies on short pulses with rapidly rising or falling edges, which usually occupy a large bandwidth in the frequency domain, reducing the spectral efficiency. Nevertheless, two methods have been proposed recently to increase the SE of an OTDM signal, including the generation of a phase-correlated OTDM signal with subsequent strict filtering for generation of optical Nyquist pulses, employing orthogonality between the thus constructed TDM channels [13,14].

The technique of *Nyquist shaping* has been widely used in wireless communication systems for signal transmission at minimum bandwidth with zero inter-symbol interference (ISI). The generated signal with almost rectangular spectrum corresponds to sinc pulses in the time domain. They have periodic zero crossings where neighboring symbols can be detected without ISI. This technique has recently been used for optical communications to generate WDM signals, where Nyquist shaping is implemented either electrically using digital signal processing (DSP) or optically using a liquid crystal-based optical filter [14–16]. If an OTDM signal is filtered by a rectangular optical filter with bandwidth equal to the baud rate (Nyquist OTDM or N-OTDM), sinc-shaped pulses are generated for all the tributaries and cross talk (XT) between OTDM tributaries can ideally be avoided at the zero crossing of neighbor pulse amplitudes at the center of each tributary [17]. Nyquist OTDM can be generated using either phase-correlated or phase-uncorrelated OTDM signals. One practical limitation in receiving Nyquist OTDM signals is that optical sampling is needed. This is because the bandwidth of a Nyquist OTDM signal is usually beyond the electronic bandwidth and the data has to be sampled exactly at the point without XT, which requires a very short switching gate. However, if the switching gate is too narrow the switched signal will experience excessive loss, resulting in a switched signal with low SNR. One solution is to use optical spectral slicing with parallel coherent detection using an optical frequency comb (OFC) as local oscillator [18,19]. Another option is to convert the time-domain signal into frequency domain using time-domain optical Fourier transformation (TD-OFT) and extract each tributary using optical bandpass filters (OBFs) [20–24]. An advantage of using OBFs instead of time-domain optical gates is that the extracted signal already has a narrow spectrum and won't experience additional filtering losses, due to the narrow filter, before it's launched into a base-rate optical receiver.

In this paper, we use polarization-insensitive TD-OFT to receive a 320 Gb/s Nyquist OTDM signal using differential-phase-shift-keying (DPSK) with a base rate of 10 Gb/s. The residual polarization sensitivity of the OTDM receiver is less than 0.5 dB. The Nyquist OTDM signal is generated by rectangular filtering of an OTDM signal with filter bandwidth equal to the signal baud rate, resulting in almost zero roll-off. In the TD-OFT based receiver, mapping between time and frequency domains can be achieved, and therefore sinc-shaped Nyquist pulses in the time domain are converted into sinc-shaped overlapped spectra in the frequency domain, resulting in a spectral shape similar to an OFDM signal. The conversion is designed so that a large channel spacing is achieved, enabling extraction of the tributaries in the frequency domain using only passive filtering. In our experiment, by adjusting the TD-OFT parameters, the Nyquist OTDM signal is converted to an OFDM-like signal with 10 GBaud subcarriers and 100 GHz channel spacing. These are then filtered by a 40 GHz rectangular filter and received using direct detection. 11 out of 32 tributaries are extracted at

the same time with a bit-error rate (BER) well above the forward error correction (FEC) limit of  $3.8\text{E-}3$ . The integrity of the entire 320 Gb/s Nyquist-OTDM signal is verified and  $\text{BER} < 1\text{E-}9$  is achieved for all the 32 tributaries.

## 2. Generation of a Nyquist OTDM signal using a Nyquist optical filter

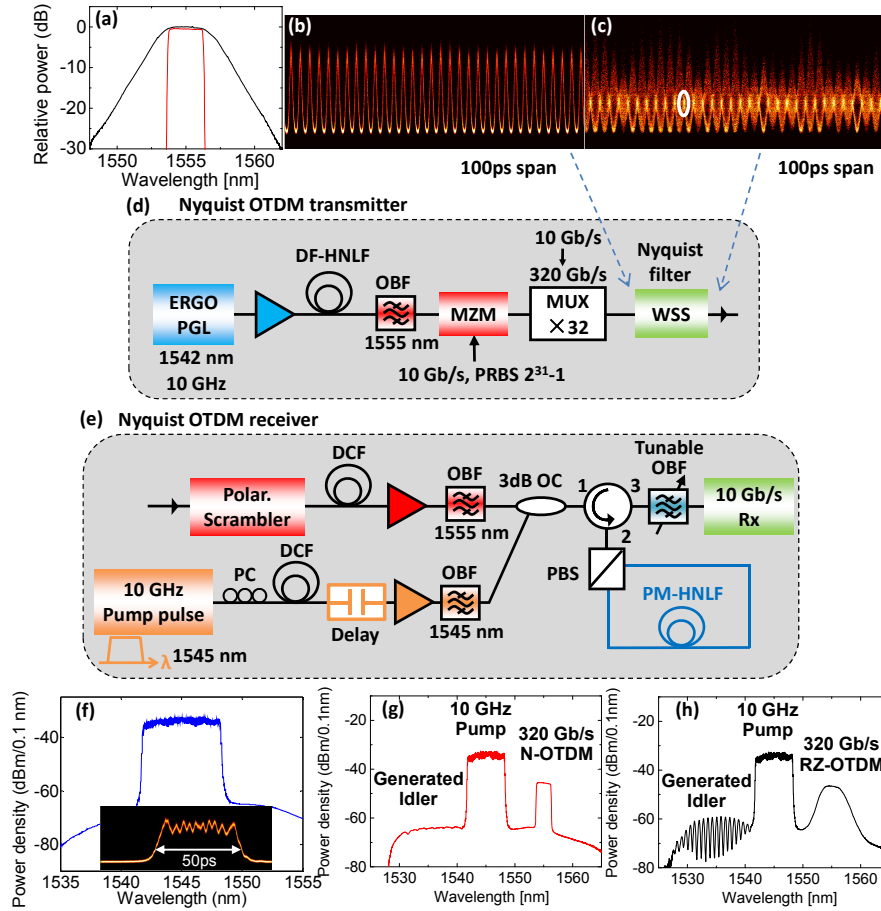


Fig. 1. Nyquist OTDM transmitter and receiver. (a) Spectra before (black) and after (red) the Nyquist filter; OSO eyediagrams before (b) and after (c) the Nyquist filter, at the center of each bit period (white circle) ICI between TDM tributaries is avoided; Experimental setup of the Nyquist OTDM transmitter (d) and polarization-insensitive Nyquist OTDM receiver (e); (f) Optical spectrum and OSO eyediagram (inset) of 10 GHz linearly chirped pump pulses; Optical spectra of the FWM output for the input signals of 320 Gb/s N-OTDM DPSK (g) and 320 Gb/s RZ-OTDM DPSK (h).

Figure 1(d) shows the experimental setup of a Nyquist OTDM transmitter, which consists of an OTDM transmitter and a Nyquist optical filter. In the OTDM transmitter, the erbium glass oscillating pulse-generating laser (ERGO-PGL) produces a pulse train with a repetition rate of 10 GHz centered at 1542 nm with 1.5-ps full-width at half-maximum (FWHM). The 10 GHz pulses are compressed and wavelength converted to 1555 nm, based on self-phase modulation (SPM) in a 400-m dispersion-flattened highly nonlinear fiber (DF-HNLF, dispersion coefficient  $D = -0.45$  ps/nm/km and dispersion slope  $S = 0.006$  ps/nm<sup>2</sup>/km at 1550 nm, nonlinear coefficient  $\gamma = 10.5$  W<sup>-1</sup>km<sup>-1</sup>) and subsequent off-center filtering with a 5-nm filter. The generated pulses at 1555 nm are DPSK encoded with a 10 Gb/s PRBS ( $2^{31}$ -1) signal in a Mach-Zehnder modulator (MZM). The modulated 10 Gb/s DPSK signal is multiplexed in

time using a passive fiber-delay multiplexer (MUX  $\times$  32) to generate a 320 Gb/s RZ-OTDM DPSK signal. The generated 320 Gb/s RZ-OTDM signal with a 20-dB bandwidth of 1.3 THz is filtered by a Nyquist filter, resulting in a 320 Gb/s N-OTDM DPSK signal with a bandwidth of 320 GHz. The spectra and optical sampling oscilloscope (OSO) eyediagrams before and after the Nyquist filter are shown in Figs. 1(a)–1(c). The N-OTDM signal eyediagram appears to be distorted due to the overlapping of neighboring channels as a result of the narrow filtering; however at the centre of each bit slot (white circle) inter-channel interference (ICI) is absent due to the sinc shape of the Nyquist filtered pulses.

### 3. Reception of a Nyquist OTDM signal based on the TD-OFT

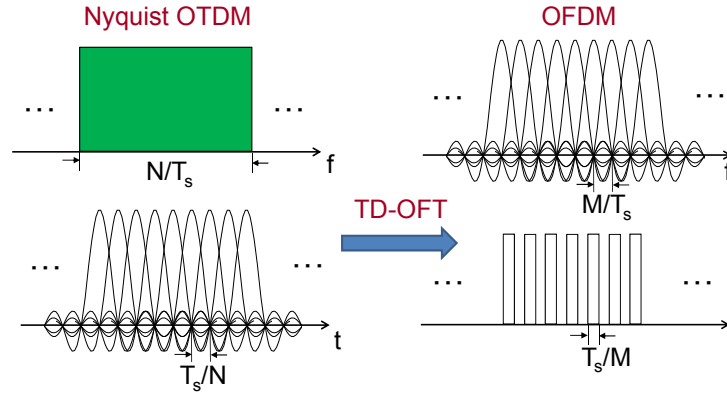


Fig. 2. Concept of interchange between time and frequency using TD-OFT (a Nyquist-OTDM can be converted into a waveform similar to an OFDM signal and the frequency spacing can be adjusted by changing the factor of M).

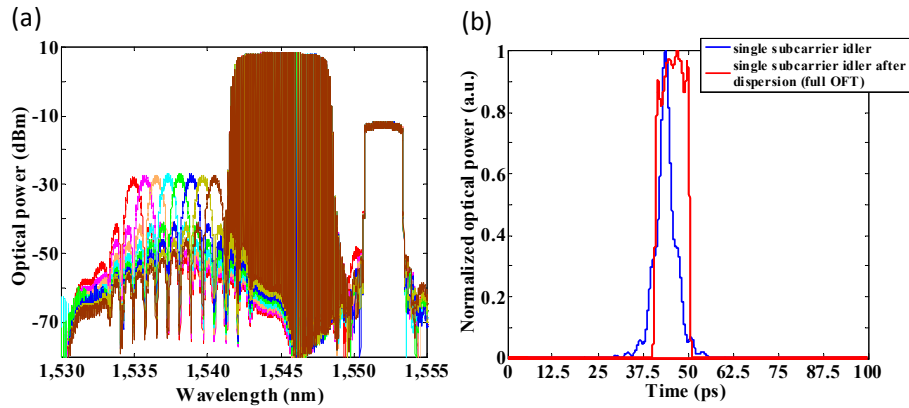


Fig. 3. Simulated results for a single N-OTDM tributary at the input of the TD-OFT. (a) Optical spectra at the output of the TD-OFT for a single OTDM tributary at different time slot, which corresponds to different OFDM subcarrier after the TD-OFT; (b) time-domain waveform of a single subcarrier as the idler before (red) and after (blue) another dispersion with a chirp rate of K.

The concept of the TD-OFT stems from the space-time duality between diffractive propagation of spatial light beams and dispersive propagation of temporal optical pulses [20–24]. Since a spatial lens can be employed to achieve a spatial Fourier transformation of an object placed at the front focal plane, a time lens can also be used to achieve a time-domain Fourier transformation of a temporal profile. The time lens equivalent of a spatial lens is a quadratic phase modulation as a function of time. This can be achieved using an E/O phase modulator [22] or a four-wave mixing (FWM) process [23,24]. The FWM process can

provide larger quadratic phase-modulation than the E/O phase modulator. In this case, the dispersed data pulses act as signal  $E_s(t)$  and phase modulation is achieved through FWM using linearly chirped (i.e. dispersed) pump  $E_p(t)$  pulses. As a result of the FWM process, the generated idler  $E_i(t)$  combines the phases of both pump and signal ( $E_i(t) \propto E_p^2(t)E_s^*(t)$ ) and acquires the pump's quadratic phase modulation on the conjugated phase of the signal.

Figure 2 shows the concept of interchange between time and frequency using the TD-OFT. A Nyquist-OTDM signal can be converted into a waveform similar to an OFDM signal and the frequency spacing can be adjusted by changing the factor  $M$ , where  $T_s$  is the bit period of the base rate signal (here 100 ps) and  $N$  is the OTDM factor (here 32). If the frequency spacing is designed to be large enough, passive filtering can be used to extract the subcarriers of the OFDM-like signal. Figure 3 shows simulated results for a single N-OTDM tributary at the input of the TD-OFT. Sinc-shaped spectra similar to an OFDM signal result from the TD-OFT of a single OTDM tributary placed at different time positions, corresponding to different time slot. At each position (time slot), the OTDM channel is converted to an OFDM subcarrier at different frequency. At the same time, a rectangular time-domain waveform could be achieved after the conversion (i.e. frequency-to-time mapping, shown in Fig. 3(b)) if a full TD-OFT is applied, which would simply require an additional amount of dispersion with a chirp rate of  $K$  (equal to the chirp rate for the input N-OTDM) at the output of the FWM stage. Note that, in our experiment the additional dispersion is not needed and hence not applied, and we obtain a narrower time-domain waveform (blue trace) at the output of the FWM. We do not need the additional dispersion, as the OFDM subcarrier will be extracted by a 40 GHz rectangular filter and then launched directly into a 10 Gb/s receiver.

Figure 1(e) shows the experimental setup of a polarization-insensitive Nyquist OTDM receiver based on the TD-OFT. In order to achieve the TD-OFT or the time-to-frequency mapping, the input N-OTDM signal propagates through a dispersion compensation fiber (DCF) having  $\beta_2 L_{DCF} = 4.972 \text{ ps}^2$  before it is launched into a 100 m polarization-maintaining highly nonlinear fiber (PM-HNLF, zero dispersion at 1545-nm and  $S = 0.025 \text{ ps/nm}^2\text{km}$ ). The desired chirp rate  $K = 1/(\beta_2 L_{DCF}) = 2\pi\Delta f/\Delta t$  depends on the temporal spacing ( $T_s/N$ ) and the targeted frequency spacing ( $M/T_s$ ). Here, the target is to map a 320 Gbaud signal with  $T_s/N = 3.125 \text{ ps}$  to a frequency spacing  $\Delta f = 100 \text{ GHz}$  (corresponding to  $M = 10$ ).

The 10 GHz pump pulses having a super-Gaussian spectrum (FWHM of 800 GHz) centred at 1545 nm are generated by off-centre filtering the same supercontinuum used for data generation. If the N-OTDM signal has been transmitted over distance before the detection, a clock recovery unit will be needed in the receiver to synchronize the pump pulse and the data signal [25]. The generated pump pulses are linearly chirped with a chirp rate of  $K/2$  by propagation through another DCF and the chirp of the pump is transferred to the idler generated in the FWM process in the PM-HNLF. Figure 1(f) shows the optical spectrum and OSO eye diagram of the 10 GHz linearly chirped pump pulses at the input of the PM-HNLF. The PM-HNLF is in a polarization-maintaining fiber loop (PMFL) with bi-directional operation for the polarization insensitive operation [26,27]. The pump polarization is adjusted by a polarization controller (PC) and launched into the polarization beam splitter (PBS) with 45° linear polarization, providing equal intensity in both directions of the loop. The FWM conversion efficiencies in both directions in the loop are therefore the same. In the PMFL, the data signals of random polarization are projected on the two polarization axes of the PBS which counter-propagate in the fiber loop. The generated idlers are coherently recombined in the PBS and sent out at port 3 of the circulator. Both outputs of the PBS are slow axis aligned to the PM-HNLF. When the polarization of the incoming data signal is scrambled, the power distribution of the data signal at the PBS outputs is changed but the total power of the generated idler will be kept constant. The launched powers into the PMFL for the data signal and pump pulses are 14 dBm and 26.5 dBm, respectively.

Figure 1(g) and 1(h) show the optical spectra of the FWM output for the input signals of 320 Gb/s N-OTDM DPSK and 320 Gb/s RZ-OTDM DPSK, respectively. The generated idler

is a time-to-frequency mapped version of the original signal. The RZ-OTDM signal with RZ Gaussian pulses in the time domain is converted into a WDM signal with Gaussian shaped spectra and frequency spacing of 100 GHz. The extinction ratio between the peak and bottom in the frequency domain is  $\sim 16$  dB. The N-OTDM signal with sinc-shaped Nyquist pulses in the time domain is converted into sinc-shaped overlapped spectra in frequency domain, resulting in a waveform similar to an OFDM signal. Since the frequency spacing (100 GHz) is much larger than subcarrier baud rate (10 Gbaud for each tributary), a tunable OBF with a bandwidth of 40 GHz is used to extract the subcarriers. The extracted 10 Gb/s DPSK tributaries are directly detected by a 10 Gb/s DPSK receiver.

#### 4. Experimental results

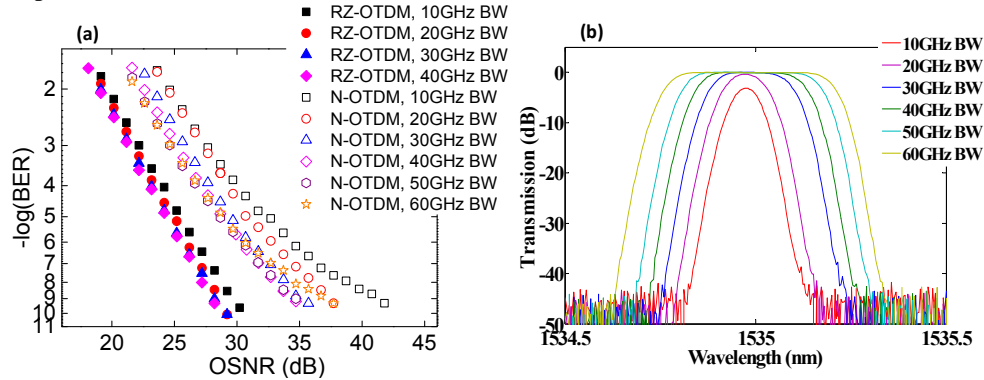


Fig. 4. (a) BER measurements for the 320 Gb/s RZ-OTDM DPSK signal and 320 Gb/s N-OTDM DPSK signal using different bandwidth (BW) filter to extract the generated idlers after the TD-OFT; (b) transfer functions of the filters with different BW (10 GHz, 20 GHz, 30 GHz, 40 GHz, 50 GHz and 60 GHz).

We first characterized the TD-OFT based receiver using a bandwidth (BW) tunable filter to extract the generated idlers and measured the bit error ratio (BER) for both 320 Gb/s RZ-OTDM DPSK signal and 320 Gb/s N-OTDM DPSK signal, as shown in Fig. 4(a). In both cases 40 GHz BW filter centered at 1533.4 nm exhibited optimum performance. The chosen bandwidth is a trade-off between minimization of inter-channel interference (ICI) and intersymbol interference (ISI). Both 320 Gb/s RZ-OTDM DPSK and 320 Gb/s N-OTDM DPSK show  $\text{BER} < 1\text{E-}9$  using the 40 GHz BW filter, although the 320 Gb/s N-OTDM signal indicates an error floor due to the residual ICI. The back-to-back OSNR sensitivity at a BER of  $1\text{E-}3$  is 21.3 dB for 320 Gb/s 33% RZ-OTDM DPSK and 25.1 dB for 320 Gb/s N-OTDM DPSK. Transfer functions of the filters with different BW are shown in Fig. 4(b).

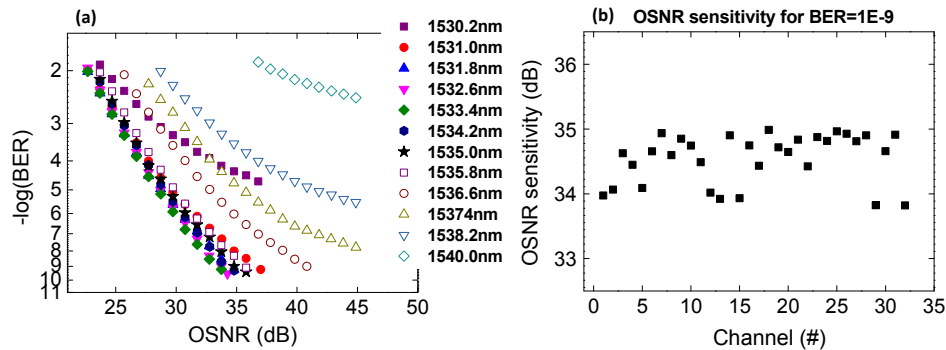


Fig. 5. (a) BER measurements for the 10 Gb/s subcarriers extracted at different wavelengths; (b) OSNR sensitivity of all the 32 OTDM tributaries at a BER of  $1\text{E-}9$ , measured by scanning the N-OTDM signal in the time domain and keeping the 40 GHz filter fixed at 1533.4 nm.



Figure 5(a) shows the BER measurements of the 320 Gb/s N-OTDM DPSK signal for the 10 Gb/s subcarriers extracted at different wavelengths using the 40 GHz tuneable filter. 12 subcarriers of 10 Gb/s at wavelengths from 1530.2 nm to 1540 nm can be extracted at the same time. 11 of them (1530.2 nm to 1538.2 nm) show the BER below  $1\text{E-}4$  and 7 of them (1531 nm to 1535.8 nm) show the BER below  $1\text{E-}9$ . The subcarriers at both edges deteriorate mainly due to the timing misalignment between the chirped data pulses and the chirped pump, since only the centre parts of the chirped data pulses can be fully covered by the chirped pump pulses. The edge parts of chirped data pulses cannot be fully covered by the chirped pump pulses, resulting in imperfect TD-OFT and performance degradation. To verify the integrity of the entire 320 Gb/s N-OTDM signal, each tributary is extracted by using the 40 GHz filter at 1533.4 nm and tuning the time delay between the pump and the data. All the 32 tributaries show  $\text{BER} < 1\text{E-}9$  and the average OSNR sensitivity at the BER of  $1\text{E-}9$  is 34.5 dB with a spread of 1.2 dB, as shown in Fig. 5(b).

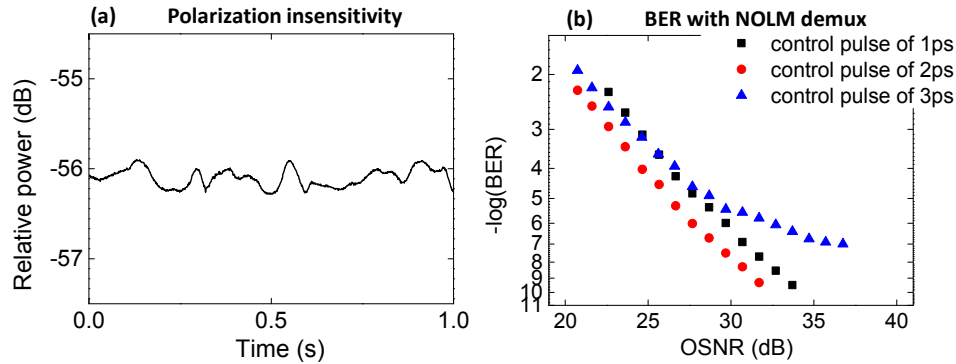


Fig. 6. (a) Power fluctuation of the generated idler with polarization scrambling; (b) BER measurements when using the NOLM to demultiplex OTDM tributaries with the control pulsewidth of 1 ps, 2 ps and 3 ps.

To characterize the residual polarization sensitivity, we measured the power fluctuation of the generated idler versus time (1 s) while scrambling the signal polarization in front of the OTDM receiver with a scan rate of 5 Hz. The maximum fluctuations are less than 0.5 dB, as shown in Fig. 6(a). To compare with the TD-OFT based OTDM receiver, a nonlinear optical loop mirror (NOLM) [12,13] is also used to demultiplex the N-OTDM signal. We measured the BER of demultiplexed OTDM tributaries with control pulsewidths of 1 ps, 2 ps and 3 ps, as shown in Fig. 6(b). Compared to the NOLM based N-OTDM receiver with the control pulsewidth of 2 ps, the TD-OFT based receiver has slightly worse performance mainly due to the relatively low FWM efficiency. If the FWM efficiency is higher, which requires either higher pump power or longer HNLF, the TD-OFT based receiver is expected to have better performance. In the NOLM based receiver, the control pulse generates a time-domain optical gate, which is used to extract the centre part of each tributary. If the control pulse is too broad, residual ISI will degrade the extracted tributary. There is an error floor when the control pulsewidth is 3 ps. If the control pulse is too short, the extracted tributary will experience too high loss, resulting in a low OSNR after the demultiplexing. Compared to the case of control pulsewidth of 2 ps, there is a 1.8 dB OSNR penalty for the case of control pulsewidth of 1 ps. The losses mentioned above have two sources. Firstly, a very short timing gate will discard a significant fraction of the power and only allow a small portion of the signal to pass. Secondly, the demultiplexed signal after the short timing gate has a very broad spectrum in the frequency domain and will be filtered by a narrow-band filter before it is launched into a base-rate receiver. If the NOLM is used to receive the N-OTDM signal with higher baud rate, the required timing gate would be even shorter and the losses due to the short timing gate will be even higher.

## 5. Conclusion

We have demonstrated the generation of a 320 Gb/s Nyquist-OTDM DPSK signal by rectangular filtering with the bandwidth equal to the baud rate, and the reception of the Nyquist-OTDM signal by polarization-insensitive time-domain optical Fourier transformation followed by passive filtering. As the result of the TD-OFT, a spectral shape similar to an OFDM signal with a large frequency spacing of 100 GHz is generated and subcarriers are extracted by a tunable 40 GHz filter. 11 subcarriers are extracted simultaneously with a BER below  $1\text{E-}4$ . The integrity of the entire 320 Gb/s N-OTDM signal is verified and  $\text{BER} < 1\text{E-}9$  is achieved for all the 32 tributaries. Less than 0.5 dB polarization sensitivity in the OTDM receiver is demonstrated using a polarization diversity scheme. Compared to a NOLM-based OTDM receiver, the TD-OFT based OTDM receiver does not rely on a very short timing gate and causes less loss due to the spectral compression in the TD-OFT process. This makes it easier to scale the scheme to higher baud rates. In addition, after the TD-OFT, only passive filtering is needed to extract all the OTDM channels, which is more power efficient than multiple active timing gates.

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